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DIRECT UTILIZATION OF CRUDE OIL AS FUEL IN U.S. ARMY FOUR-CYCLE--ETC(U)
AUG 78 J V MOFFITT, E A FRAME DAAG53-76-C-0003

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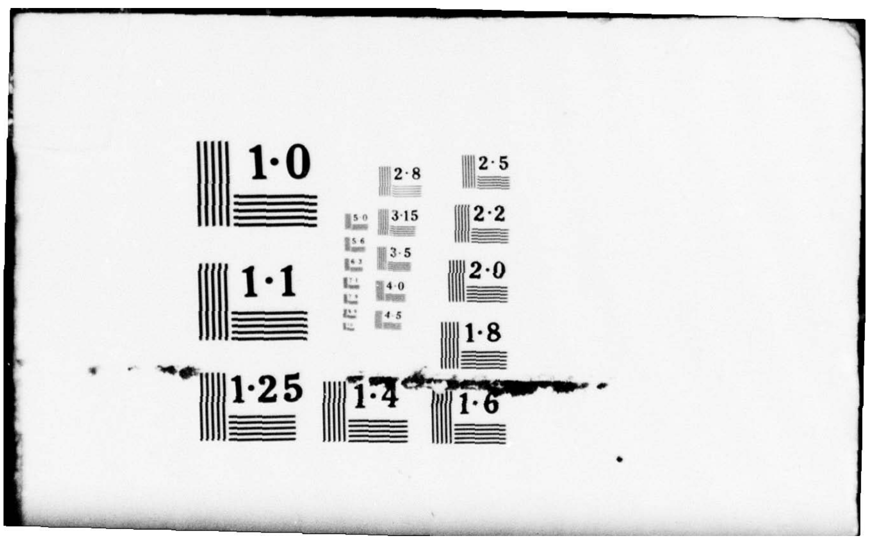
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DIRECT UTILIZATION OF CRUDE OIL AS FUEL IN U.S. ARMY FOUR-CYCLE DIESEL ENGINE MODEL LDT-465-1C

INTERIM REPORT
AFLRL No. 108

by

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and

Edwin A. Frame

prepared by

U.S. Army Fuels and Lubricants Research Laboratory
Southwest Research Institute
San Antonio, Texas

under contract to

U.S. Army Mobility Equipment Research and Development Command
Fort Belvoir, Virginia

Approved for public release; distribution unlimited

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August 1978

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Performance curves for the U.S. Army LDT-465-1C engine were obtained using DF-2 and crude oils of varying properties. A cyclic endurance test was run using crude oil as the fuel. The results of the crude oil fueled test were compared to test where DF-2 fuel was used. The crude oil resulted in significantly more engine wear and deposition than the DF-2. With crude oil fuel, the lubricant was severely degraded at end of test.

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FOREWORD

The work reported herein was conducted at the U.S. Army Fuels and Lubricants Research Laboratory (USAFLRL), located at Southwest Research Institute, San Antonio, Texas under Contracts DAAG53-76-C-0003 and DAAK70-78-C-0001 during the period April 1977 through August, 1978. The contract monitor was Mr. F.W. Schaekel, USAMERADCOM, DRDME-GL, Fort Belvoir, Virginia.

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I. Introduction

The U.S. Army, in maintaining the national security, must be able to operate its fleet of combat vehicles throughout the world. This could often require long supply lines for vehicle fuels, particularly when considering the current world-wide energy situation which could result in severely restricted local procurement. An earlier project was conducted for MERADCOM (ref-1&2) to assess the feasibility of direct utilization of crude oil as an emergency energy source. In this program, a single cylinder 4-cycle diesel engine (TACOM ER-3) was used to run 120 hour endurance tests using crude oil as the fuel. The results of this investigation were very encouraging as one crude oil resulted in very similar engine condition as when a standard diesel fuel (reference DF-2) was used. The use of a crude oil of higher sulfur content and lower API gravity resulted in increased deposits and wear, but no major engine problems developed in the 120 hours of direct crude oil utilization. Recently, a steady-state endurance test was made in the U.S. Army aluminum block 6V53T two-cycle diesel engine (M-551) using a high sulfur crude oil (1.7%wS) as the fuel (ref-3). This test completed 166 hours before being terminated due to power loss caused by a burnt valve. This report addresses the direct utilization of crude oil by a multicylinder production type U.S. Army engine of four-cycle design.

I.A. U.S. Army LDT-465-1C Multifuel Engine

The tests were conducted in the LDT-465-1C multifuel engine (M-44A2). This diesel engine is of four-cycle design and displaces 7.8 liters (478 cu. in.). It has M.A.N. combustion chamber design and uses a density compensated Bosch fuel injection pump. In this turbocharged configuration, annulus pistons were used. The engine was operated on a 168-kilowatt (225-Bhp) eddy-current dynamometer and in this configuration produced about 104 kW (140 bhp) when using DF-2.

II. Engine Performance Comparisons Using Crude Oils and DF-2

Variable speed runs at full-rack were conducted in the four-cycle LDT-465-1C multifuel engine using reference DF-2 and four different Texas crude oils which are representative of high production rate crudes on a world-wide basis. The purpose of these full-rack runs, which covered the speed range of 1400 to 2600 rpm in 200 rpm increments, was to compare the performances of these crudes with that of conventional DF-2 in this Army engine. The properties of DF-2 are compared to those of the four crude oils, i.e., North Alazan (AL-5250); KMA (AL-5277); TXL (AL-5283); and Pearsall (AL-6846), in Table 1.

TABLE 1. TEST FUELS PROPERTIES

Oilfield	--	N. Alazan	KMA	TXL	Pearsall
AL-	DF-2	5250	5277	5283	6846
Gravity, API°	33.2	41.8	41.2	37.2	26.0
KVIS @ 38°C, cS	3.2	2.0	2.6	4.6	37.6
Sulfur w%	0.42	0.06	0.20	0.43	1.7
GC BP Distribution w% off @ °C					
10%	242	112	97	97	176
50%	271	244	301	319	501

In the LDT-465-1C performance comparisons of DF-2 and the four crude oils, the fuel density compensator on the engine was adjusted to yield a full-rack flow rate of 29.5 kg/h of DF-2 at 2600 rpm. No further adjustment to the density compensator was made throughout the variable speed evaluations of DF2 and the crude oils. Moreover, the standard configuration of the engine was neither modified nor altered for these tests. The engine lubricant was a mineral based, SAE viscosity grade 30 product conforming to specification MIL-L-2104C (Lubricating Oil, Internal Combustion Engine, Tactical Service).

The results of these variable speed, engine performance comparisons runs are graphically depicted in Figure 1 in which observed brake power and brake specific fuel consumption (BSFC) are plotted against engine speed. Under the conditions of these LDT-465-1C engine tests, the data indicate that both the brake power and BSFC with North Alazan crude (AL-5250) compared most favorably overall to the values obtained with DF-2 at equivalent engine speeds. From 1400 to 2400 rpm, the KMA crude (AL-5277) yielded only slightly lower full-rack power that DF-2 and, at 2600 rpm, the available power was equal to that of DF-2. The specific fuel economy of the KMA crude at 1600 rpm was better than that of DF-2 or any of the other three crudes, and, at 2600 rpm was equal to that of DF-2. On the other hand, the Pearsall crude (AL-6486) gave significantly lower power and poorer economy over the entire speed range than DF-2 or any of the other crudes at equivalent speeds. The performance of the TXL crude (AL-5283) fell between that of AL-5277 and AL-6486. The serpentine nature of all the curves shown in Figure 1, including those for DF-2, is tentatively attributed to fuel injection and/or turbocharging characteristics peculiar to the LDT-465-1C engine, while the differences in the fuel's performance at any given speed probably indicate the effects of fuel property differences on combustion efficiency at the fixed setting of the fuel density compensator.

Based on the findings of these fuel performance comparisons, it appears that the North Alazan crude (AL-5250) and possibly the KMA crude (AL-5277) might be satisfactorily substituted for DF-2 in fueling the LDT-465-1C engine without appreciable performance change, but only in emergency situations. While none of these crudes are presently available in quantities sufficient to meet military supply requirements, the results can be extrapolated to include any other crudes throughout the world which have similar properties.

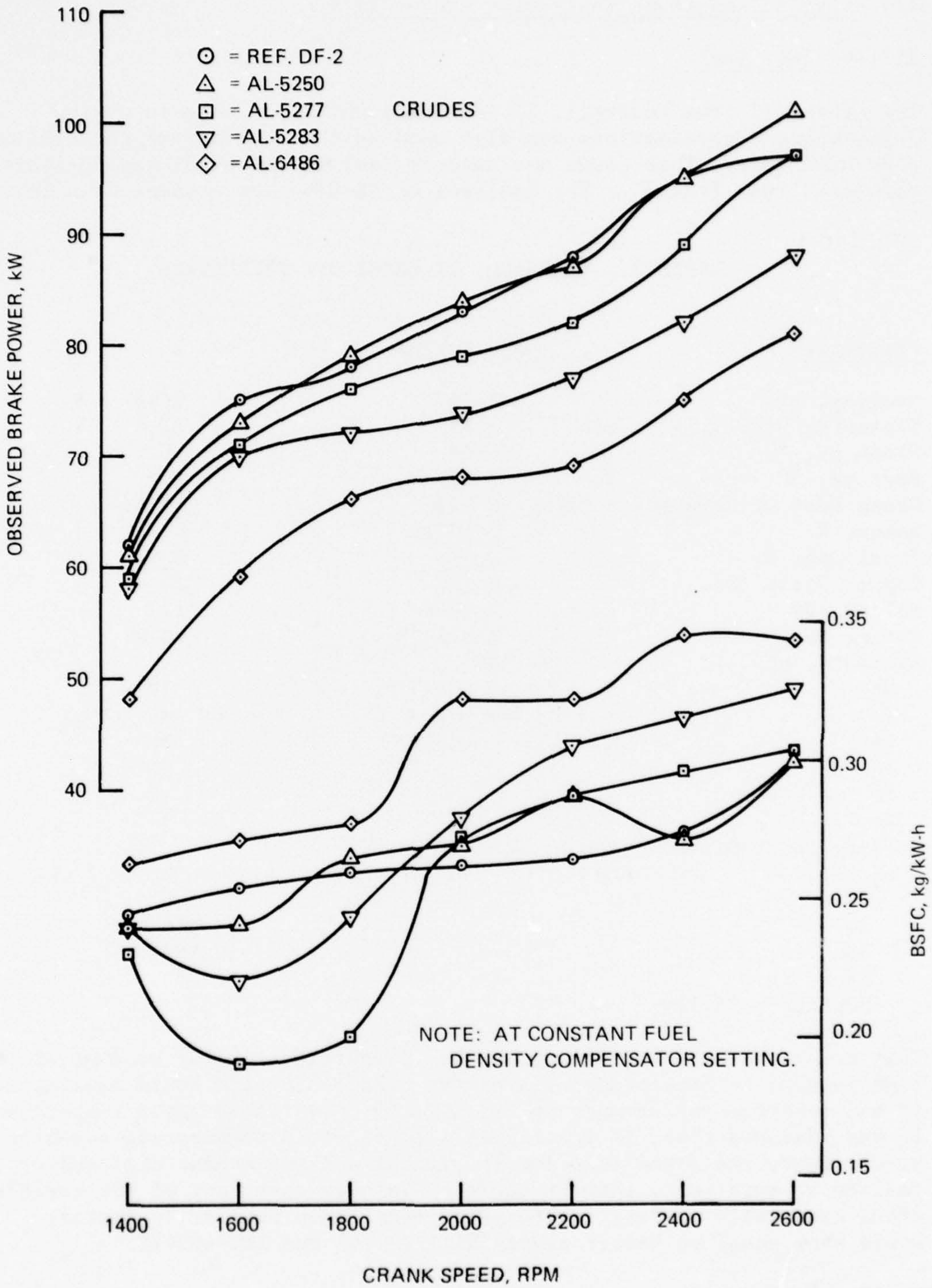


FIGURE 1. FULL-RACK PERFORMANCE COMPARISON OF CRUDE OILS AND REF. DF-2 IN AN LDT-465-1C MULTIFUEL ENGINE

III. Cyclic Endurance Test Using Crude Oil

III.A. Test Fuel

The crude oil from Pearsall, TX (AL-6846) which was used in making performance determinations was also used as the fuel during the cyclic endurance test. This crude was used as fuel in the 6V53T steady-state endurance test (ref-3). The analyses of AL-6846 are presented in Table 2.

TABLE 2. PEARSALL, TX CRUDE OIL PROPERTIES

Properties	ASTM Method	
Gravity, API°	D 287	26.0
Kinematic Vis, @ 38°C, cSt	D 445	37.6
Flash pt, °C	D 93	0
Pour pt, °C	D 92	-10
Gross Heat of Combustion MJ/kg	D 240	43.41
Water, %	D 1744	0.11
Total Ash, %w	D 482	0.02
Copper Strip Cor.	D 130	1B
Sulfur, %w	D 1266	1.7
Cetane No.	D 613	40.0
Elements, ppm	AA	
Ni		10
V		95
Ca		5
Al		50
Si		10
Fe		5
Boiling Point Distribution by GC		
w% off		°C
10		176
20		266
50		501
60		569
Residue = 36.1%w		

This crude was selected because it has properties similar to many of the high production rate crude oils of the Middle East and South America and it had inferior performance in the LDT-465-1C variable speed comparisons. It was reasoned that, if the Pearsall crude would demonstrate acceptable power, wear, and deposition levels without causing engine distress or failure in this test, then it could be assumed that many of the world's other crude oils of less severe properties, when similarily tested, would show equal or better compatibility with the LDT-465-1C.

III.B. Test Lubricant

The test lubricant used was REO 203, grade 30 which is of MIL-L-2104C (ref-4) quality level. Properties of this lubricant are summarized in Table 3.

TABLE 3. TEST LUBRICANT REO 203

Property	ASTM Method	New Oil
K. Vis. cS, 38°C (100°F)	D 445	121.6
K. Vis, cS, 99°C (210°F)	D 445	12.6
VI	D 2270	103
TAN	D 664	2.97
TBN	D 2896	5.08
Insolubles, wt%	D 893	
Pentane A		0.05
Benzene A		0.04
Pentane B		0.03
Benzne B		0.02
API Gravity, °	D 287	27.4
Pour Point, °C	D 97	-21
Flash Point, °C	D 92	241
Carbon Residue, wt%	D 524	1.19
Sulfated Ash	D 874	1.01
Elemental	Method	
Ba, ppm	AA	NIL
Mg, ppm	AA	NIL
Ca, wt%	AA	0.24
Zn, wt%	AA	0.09

This lubricant was selected to permit comparison of this test with a previous test which used reference DF-2 and followed the same endurance test procedure (ref-5).

III.C. Test Method

The endurance procedure chosen to evaluate the direct utilization of AL-6486 crude oil in the LDT-465-1C engine was the Army/CRC Wheeled-Vehicle Cyclic Test (ref-6). This 210-hour, laboratory dynamometer procedure is designed to simulate approximately 32,180 kilometers (20,000 miles) of military wheeled-vehicle operation on the proving ground and thus provide a meaningful assessment of fuel/lubricant/engine compatibility. The test cycle consisted of alternating periods of full-power and cold idling with an overnight shutdown. Table 4 shows the test cycle conditions used.

TABLE 4. WHEELED-VEHICLE TEST
Cycle/Day for 15 Days

Period	Time, hrs	Load, %	RPM	Coolant Temp, °C
1	2	100	2600	82
2	1	0	850	38
3	2	100	2600	82
4	1	0	850	38
5	2	100	2600	82
6	1	0	850	38
7	2	100	2600	82
8	1	0	850	38
9	2	100	2600	
10	10	--------Overnight Shutdown---------		
	24			

The complete test is 15 days at 14 hours/day operation for a total of 210 hours.

III.D. Fuel System Modifications

Prior to starting the test with the Pearsall crude, the fuel system was modified to enable preheating the crude to about 60°C before it entered the primary filter and thereby reduce the possibility of wax clogging of the filter element. The modifications were as follows: A clean 18.9 liter (55 gallon) steel drum, serving as a fuel heater/weigh tank was equipped with fuel inlet and outlet fittings, an immersion thermocouple, and a thermoswitch through its lower sidewall. The top end of the drum was fitted with an atmospheric vent, then the external two-thirds of the sidewall were wrapped with several turns of electric thermal tape, which was connected, through the thermoswitch, to a 110-VAC source. The entire drum, except the bottom end, was then insulated with fiberglass, after which the drum was placed upright on a platform scale located about 1.5 meters from the engine bedplate. The two fuel filters on the engine block were bypassed, and instead, two identical filters were mounted on an upright bracket located at the edge of the bedplate nearest the fuel heater drum. To maintain the elevated fuel temperature through both filters, the secondary filter was wrapped with electric thermal tape to provide boost heat, if required, and a thermocouple and thermoswitch were externally attached to the filter wall. To monitor filter clogging, three pressure gauges were installed: one each at the primary filter inlet, between the primary and secondary filter, and at the outlet of the secondary. Flexible fuel supply and return lines were installed between the weigh drum outlet and the engine pump, while conventional tubular lines were installed between the pump and filters and between the flters and the fuel distribution unit. The supply line from the weigh drum to the pump and filters, as well as the filters themselves, were insulated with fiberglass, and a fuel shutoff valve was installed at the fuel inlet to the weigh drum. The test crude was supplied, prefiltered to the weigh drum from a mobile tanker parked outside the laboratory. These special fuel system changes constituted the only modifications to an otherwise standard laboratory configuration of the engine and its ancillary systems.

III.E. Fuel Density Compensator Adjustment

Upon completing the preceding modifications to the fuel system, the engine oil sump and lubrication system were charged with REO 203, MIL-L-2104C, grade 30 lubricant. The fuel weigh drum was filled to about two-thirds of its capacity with test crude AL-6846, and the combined weight of the drum and fuel noted. Heat supply to the fuel weigh drum was then turned on and the thermoswitch was adjusted to hold the temperature of the contained fuel at 60°C. When the fuel temperature stabilized at the set-point, the engine was started and warmed up to 2600 rpm and full-rack conditions, at which time the fuel flow rate was noted. The engine was then stopped and the fuel density compensator was adjusted in an effort to obtain the same flow rate with the AL-6846 crude at 2600 rpm and full-rack as the 29.6 kg/h obtained with DF-2 under the same conditions. After a few similar adjustments of the compensator, the desired flow rate of the test crude was achieved and no further readjustments were made throughout the subsequent evaluations of that fuel.

III.F. Conduct of Test

Using AL-6846 crude, a variable speed, full-rack run was then conducted to determine the brake power output and BSFC of the LDT-465-1C engine at zero hours of the 210-hour endurance test. As indicated in Figure 2, data were taken in 200 rpm increments over the range of 1400 to 2600 rpm, inclusive. The average fuel temperature at the primary filter was 59.7°C for this power calibration run. When compared to Figure 1, these data show that AL-6846 crude still produced significantly lower brake power and poorer specific fuel economy than the reference DF-2 over the same speed range.

After completing the pre-test power calibration, the engine was started on the 210-hour cyclic endurance evaluation of AL-6846 crude. The daily cyclic schedule (Table 4) required alternate operation for two hours at 2600 rpm, full-rack and 82°C jacket coolant out and one hour at 850 rpm, no load and 38°C jacket coolant-out, for a total of 14 hours. A maximum of 10 minutes was allowed for coolant temperature reduction after each two-hour power mode. Just prior to shutdown at the end of each 14 hours, a "hot", used oil sample was withdrawn from the engine gallery for analysis. One minute after shutdown the sump oil level was determined by dipstick, and new, weighed oil was added, as required, to restore the original level. Table 5 contains the summarized engine operating data as well as the overall average hourly oil consumption for this test.

Upon completing 56 hours, the test was tentatively terminated when it was observed that the pressure differential across the primary fuel filter had apparently increased from essentially zero to about 620 kPa, thus indicating severe clogging of the element despite preheating of the fuel. Moreover, during the same period the observed brake power (at 2600 rpm) had decreased 6.0%. After withdrawing an oil sample from the gallery, the engine was stopped, and the lubricating system was drained in anticipation of engine teardown and inspection. Analysis of the oil

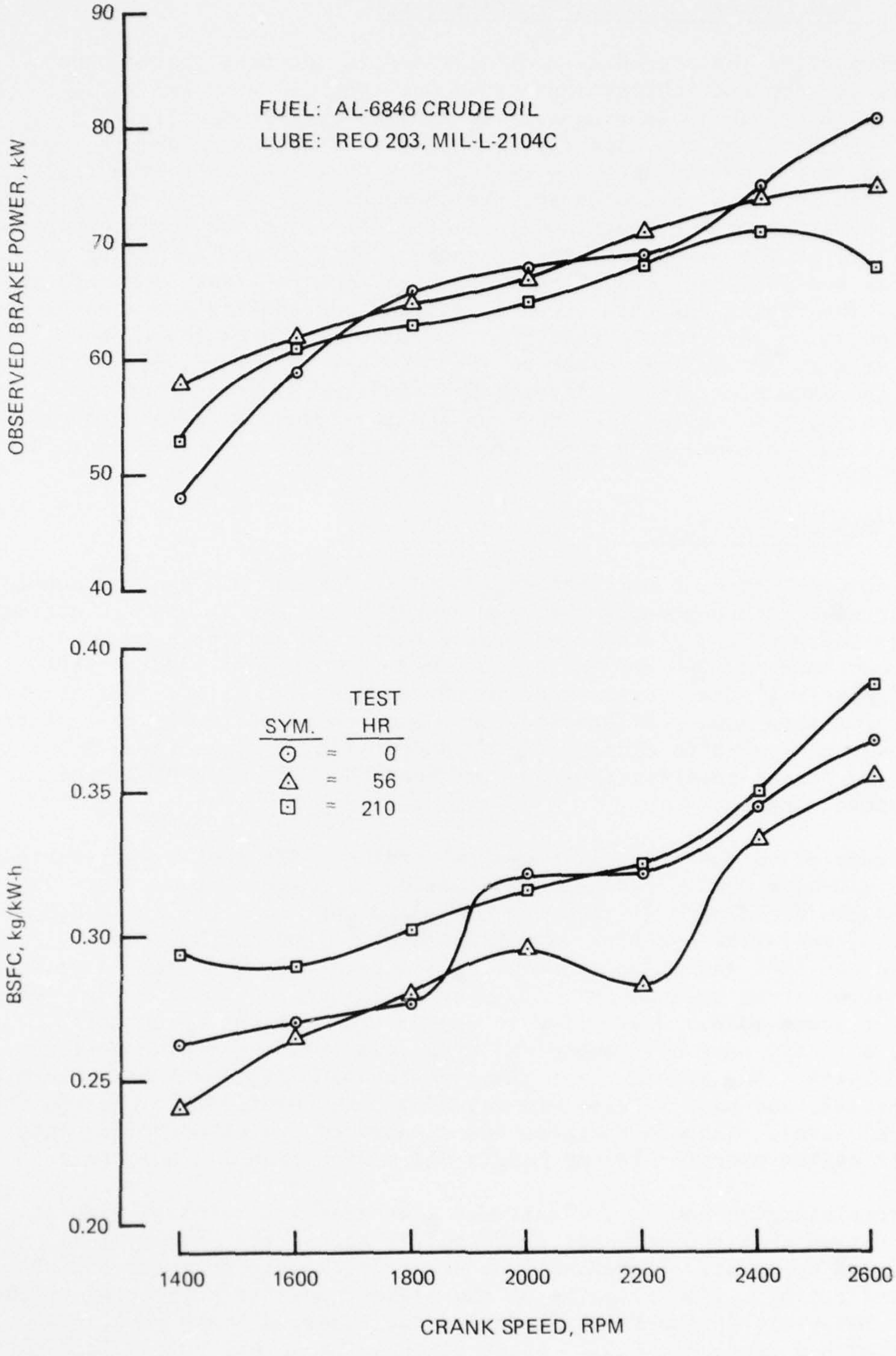


FIGURE 2. LDT-465-1C ENGINE POWER CHECKS AT FULL RACK

TABLE 5. 210-HOUR WHEELED VEHICLE CYCLIC TEST

Engine: LDT-465-1C Fuel: Pearsall (TX) Crude (AL-6846)
Lubricant: REO 203

Summary of Operating Conditions

	Power Mode			Idle Mode
	Min.	Max.	Avg.	Avg.
Speed, rpm	2600	2600	2600	850
Obs. Brake Power, kW	64.9	79.3	73.6	
Fuel Rate, kg/h	25.3	29.0	26.9	
Blowby Rate, M^3/h (at 28.3°C and atmospheric press.)	6.79	8.93	8.10	
Temperatures, °C				
Jacket Coolant-in	76.0	77.1	76.6	
Jacket Coolant-out	81.6	83.3	82.1	37.7
Fuel (at primary filter inlet)	52.2	67.7	59.9	56.1
Intake Air (at filter)	26.6	43.3	35.5	
Sump Oil	103	110	107	51.1
Int. Manifold Air	102	115	108	
Exhaust (before turbo)	582	676	615	
Exhaust (after turbo)	493	543	510	
Pressures (observed)				
Main Oil, kPa	317	400	365	401
Intake Manifold, Pa	308	370	331	
Exhaust Manifold, Pa	370	427	397	
Oil Consumption, kg/h			0.0625	

sample by X-ray fluorescence (XRF) showed an iron accumulation of 250 parts per million (ppm). At that point, it was discovered that the fuel filter had not clogged, but rather the filter inlet pressure gauge had failed. Therefore, after installing a new gauge and replacing both fuel filter elements, the lubrication system was recharged with fresh REO 203, and an interim, variable speed, full rack power curve was conducted with the test fuel to confirm the previously observed power loss. The resultant brake power and BSFC data obtained in the interim calibration run are also plotted in Figure 2. By comparison of these data with those of the initial calibration at zero test hours, it can be seen that, at 2600 rpm, the power obtained in the interim run was 6.0 kW (7.4%) lower, although the BSFC was slightly better. In view of these differences, it was decided to inspect the injector tips and combustion chambers for possible excessive deposit buildups or other distress. Upon removing the cylinder heads, it was observed that the injector tips and cylinder liner walls were in good condition but a relatively thick layer of hard, carbonaceous-like deposit had accumulated in the piston combustion bowls. After cleaning the bowls, the cylinder heads were reinstalled, and, following a brief engine warmup to retorque the head bolts and adjust valve and injector tappet clearances to standard, the endurance evaluation of the Pearsall crude (AL-6846) was resumed from 56 hours. During the first two-hour power mode of operation following resumption of the test, it was noticed that the brake power level was only 2.3% lower and the BSFC 1.4% higher than during the corresponding period at start of test. Since these differences were small, they were attributed to normal experimental error.

With the exception of two additional failures of the pressure gauge at the inlet to the primary fuel filter, one at 126 test hours and the last at 140 test hours, the endurance run was continued to 196 hours without interruption, although the average daily brake power output gradually deteriorated about 9.8% and the iron content in the lubricant as determined by XRF analysis increased to 375 ppm, compared to the values shown at 56 hours. Because of the power loss (without indication of fuel filter clogging) and the high increase of iron in the oil, it was decided to remove the cylinder heads and inspect for deposit increase in the piston bowls and distress of the injectors. The piston bowls contained only moderate deposits, which were subsequently removed, and the fuel discharge pressures required for the injectors were acceptable. After reinstalling the cylinder heads and repeating the procedure of retorquing the head bolts and adjusting the proper tappet clearances, the test was completed to its scheduled 210 hours. During this final 14-hour period, the average brake power suffered an additional 3.0% loss and the iron in the oil rose to 380 ppm with no indication of fuel filter clogging.

III.G. Results

Table 6 shows the post-test deposit ratings of the cylinders, valves, pistons, and piston rings. The cylinder ratings, which included the areas above, within, and below piston ring travel, indicated no lacquered areas in any of the liners, but indicated an average of 97.5% carbon coverage above ring travel, while the average glazing in the ring travel area was 7%. There were no stuck or sluggish valves, and their

TABLE 6. 210-HOUR WHEELED VEHICLE CYCLIC TEST

ENGINE: LDT-465-1C FUEL: Pearsall(TX)Crude (AL-6846)
LUBRICANT: REO 203

DEPOSIT RATING DATA

Cylinders, % of Area Covered

Area	Type	Cylinder No. 1	2	3	4	5	6	Avg
Above ring travel,	Lacq.	0	0	0	0	0	0	0
	Carbon	25	100	100	100	100	100	97.5
Ring travel,	Lacq.	0	0	0	0	0	0	0
	Carbon	0	0	0	0	0	0	0
	Glazing	10	15	5	2	5	5	7
Below ring travel,	Lacq	0	0	0	0	0	0	0
	Carbon	0	0	0	0	0	0	0

Valves, Demerits

Valve	Cylinder No. 1	2	3	4	5	6	Avg
Intake	2.0	1.0	3.5	2.8	2.5	3.0	2.5
Exhaust	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Pistons, WTD*

Piston No. 1	2	3	4	5	6	Avg
332	448	465	451	457	417	428

Piston Grooves, % Ring Supporting Carbon

Groove	Piston No. 1	2	3	4	5	6	Avg
Top	6.3	42.5	56.3	0	96.3	1.3	33.8
No. 2	100.0	95.0	70.0	75.0	50.0	96.3	81.1

Compression Rings, Avg. % of Upper, Lower&Inside Areas

Ring	Type Deposit	Piston No. 1	2	3	4	5	6	Avg
No. 1	Lacq.	6.7	1.7	13.3	0	15.0	0	6.1
	Carbon	33.3	33.3	20.0	33.3	0	33.3	25.5
No. 2	Lacq.	5.7	13.3	3.3	25.0	41.7	20.0	18.2
	Carbon	33.3	20.0	30.0	16.7	10.0	0	18.3
No. 3	Lacq.	13.3	0	1.7	28.3	5.0	0	8.1
	Carbon	33.3	33.3	33.3	33.3	33.3	33.3	33.3

* = Weighted Total Deposits

Oil Ring Slots, % Open

All ring slots 100% open

deposit ratings, based on demerits, showed the intake valve deposits averaged five times those of the exhaust valves, but, overall, both sets were relatively clean. The pistons' weighted total deposits (WDT) ratings ranged from 332 (piston No. 1) to 465 (piston No. 3) and averaged 428, where 900 represents the maximum possible lacquer and carbon deposit. Only the top two compression ring piston grooves were rated for percent of ring supporting carbon fill. In these ratings, the top (No. 1) groove averaged 34% while the second groove averaged about 2.4 times as much at 81%. The average percentages each of lacquer and carbon deposits on the upper, lower, and inside areas of each of the three compression rings were determined, from which an overall average for each type of deposit across a given ring number was calculated. In general, these ratings showed the average percent of lacquer coverage was lower than that of carbon, which was mostly found on the inside area of the rings. No oil ring clogging was found.

As shown in Table 7, wear measurements were confined to cylinder bore and piston ring end gap increases. The cylinder bores were measured in relation to the position of the top piston ring at top dead center (TDC), 90 deg., and bottom dead center (BDC). From these data it is evident that liner wear in this test, as might be expected, generally decreased from the transverse axis to the longitudinal, and from the TDC position of the top ring to the BDC position. It is also apparent in the table that piston ring wear, as reflected in end-gap increases, was modest. These increments were determined by comparison of ring end gaps in a standard gauge block at engine assembly and teardown.

The post-test surface conditions of the cylinder bores, valves and valve gear, pistons, connecting rod bearings and journals, piston pin bushings, and piston ring faces are described in Table 8. The cylinder bores had light scratches over and below the ring travel areas, but there was no evidence of scuffing or scoring. All intake and exhaust valves were free in their guides and, with the exception of light pitting and slight discoloration of their faces, were normal in appearance. The valve gear, which included valve and injector tappets, rocker arms, and cam lobes, was normal. The crowns and combustion bowls of the pistons were not rated for appearance because of the interim cleanups of those areas. Of the bearings and journals only those of the connecting rods were inspected for appearance. All of the connecting rod journals were normal, but No. 1 rod bearing displayed light scratches, some discoloration and imbedment of small copper flakes, while the remaining five rod bearings were also lightly scratched and discolored, but also showed partial severe wear. All piston pin bushings appeared normal. The faces of all compression and oil control piston rings evidenced no burning, scuffing, or other distress, and all rings were found free in the piston-ring grooves.

Table 9 contains data concerning the degradation of the engine lubricant, REO 203, throughout the 210-hour evaluation of AL-6846 crude in the LDT-465-1C engine as determined by conventional ASTM methods, X-ray fluorescence (XRF) and gas chromatographic (GC) analyses of periodic used oil samples. The obvious discontinuities in the data between test hour 56 and 70 were due, of course, to the oil change performed immediately following hour 56. It should be noted in appraising these

TABLE 7. 210-HOUR WHEELED-VEHICLE CYCLIC TEST

ENGINE: LDT-465-1C FUEL: PEARSALL(TX) CRUDE (AL-6846)
LUBRICANT: REO 203

WEAR DATA

Cylinder Bore Increase, mm

	Cylinder No.						
Longitudinal	1	2	3	4	5	6	Avg
Top Ring Pos.							
@ T.D.C.	0.020	0.058	0.020	0.046	0.028	0.025	0.033
@ 90 deg.	0.018	0.010	0.003	0.010	0.018	0.018	0.013
@ B.D.C.	0.015	0.013	0.005	0.013	0.015	0.015	0.011
Transverse							
Top Ring Pos.							
@ T.D.C.	0.038	0.041	0.041	0.036	0.046	0.030	0.039
@ 90 deg.	0.028	0.020	0.018	0.018	0.018	0.020	0.020
@ B.D.C.	0.020	0.015	0.010	0.013	0.013	0.033	0.017
Avg. Long&Trans							
Top Ring Pos.							
@ T.D.C.	0.029	0.050	0.031	0.041	0.037	0.028	0.036
@ 90 deg.	0.023	0.015	0.011	0.014	0.018	0.019	0.017
@ B.D.C.	0.018	0.014	0.008	0.013	0.014	0.024	0.014

Piston Ring End Gap Increase, mm

	Piston No.						
	1	2	3	4	5	6	Avg
Top Ring	0.203	0.152	0.229	0.102	0.152	0.178	0.169
No. 2 Ring	0.051	0.102	0.102	0.102	0.102	0.127	0.098
No. 3 Ring	0.102	0.076	0.051	0.152	0.051	0.102	0.089
No. 4 Ring (oil)	0.305	0.279	0.305	0.305	0.254	0.356	0.301

TABLE 8. 210-HOUR WHEELED-VEHICLE CYCLIC TEST

ENGINE: LDT-465-1C FUEL: PEARSALL(TX) CRUDE (AL-6846)
LUBRICANT: REO 203

SURFACE CONDITIONS OF PARTS

Cylinder Bores

Ring Travel Area	=	light scratches on all cyls.
Below Ring Travel Area	=	light scratches on all cyls.

Valves	Intake	Exhaust
Freeness in Guide	all free	all free
Heads	all normal	all normal
Faces	(1)	(1)
Seats	all normal	all normal
Stems	all normal	all normal
Tips	all normal	all normal

(1) = light pitting and discoloration

Valve Gear	Intake	Exhaust
Tappets	all normal	all normal
Rocker Arms	all normal	all normal
Cams	all normal	all normal

Pistons	
Top Lands	all normal
Skirts	all normal
Pins	all normal

Bearings & Journals	Bearing No. 1	2	3	4	5	6	7
Main-Bearing	not inspected						
-Journal	not inspected						
Rod-Bearing	(1)	(2)	(2)	(2)	(2)	(2)	---
-Journal	all normal						---
Piston Pin Bushing	all normal						---

(1) = Lt scratches, discolored and small Cu flakes imbedded
(2) = Lt scratches, discolored and partially worn through to show Cu

Ring Faces/Condition in Grooves

Top Rings - All normal/all free
No. 2 Rings - All normal/all free
No. 3 Rings - All normal/all free
No. 4 Rings - All normal/all free

TABLE 9. SUMMARY OF LUBRICANT DEGRADATION DATA

Test: 210-HR WHEELED VEHICLE CYCLIC. Engine: LDT 465-1C. Fuel: PEARSALL (TX) CRUDE (AL-6846). Lube: REO 203

Test Hours		(New Oil) 0	14	28	42	56	70	84	98	112	126	140	154	168	182	196	210
Kin. Vis., cSt., @ 37.7°C	(D445)	121.6	133.8	147.0	ND	182.3	125.3	ND	154.7	ND	184.6	199.4	ND	236.2	ND	276.7	309.6
Kin. Vis., cSt., @ 98.8°C	(D445)	12.61	13.74	14.75	ND	19.02	13.07	ND	15.79	ND	19.38	22.13	ND	22.75	ND	28.02	31.66
TAN	(D664)	2.97	3.00	3.79	4.11	4.00	3.36	ND	3.61	ND	4.42	4.93	ND	6.03	ND	6.72	8.80
TBN	(D2896)	5.08	4.14	4.13	4.25	3.72	4.84	ND	4.25	ND	3.05	2.07	ND	1.70	ND	1.76	1.51
Sulfated Ash, %	(D874)	1.01	ND	ND	ND	ND	1.10	ND	ND	ND	ND	1.25	ND	ND	ND	ND	1.36
Insolubles, %																	
Pentane B	(D893)	0.03	ND	ND	ND	ND	0.88	ND	ND	ND	ND	5.72	ND	ND	ND	ND	10.85
Benzene B	(D893)	0.02	ND	ND	ND	ND	0.74	ND	ND	ND	ND	4.54	ND	ND	ND	ND	9.48
Gravity, API @ 16°C	(D287)	27.4	ND	ND	ND	ND	28.7	ND	ND	ND	ND	23.1	ND	ND	ND	ND	20.4
Sulfur, % (by XRF)		0.46	ND	ND	ND	0.74	0.53	ND	0.64	0.68	0.73	0.77	0.84	0.95	0.90	0.97	0.94
Fuel Dilution, % (by GC)		0	ND	ND	ND	0.80	0.50	ND	ND	ND	ND	0.60	ND	ND	ND	ND	0.80
Metals, ppm (by XRF)																	
Fe		< 10	95	140	190	250	40	80	105	140	155	205	240	270	330	375	380
Cu		< 10	< 10	<10	40	55	<10	< 10	30	40	45	55	60	70	95	85	65
Cr		< 10	< 10	<10	< 10	<10	<10	< 10	<10	< 10	90	<10	< 10	90	< 10	< 10	< 10
Ni		ND	< 10	<10	< 10	<10	<10	10	10	10	10	10	< 10	10	10	10	10
V		ND	< 30	<30	< 30	<30	<30	< 30	30	30	30	30	< 30	30	30	30	30
Pb		ND	ND	ND	ND	100	<70	< 70	<70	< 70	< 70	<70	< 70	< 70	< 70	100	90
IR Trace No.		1350					1288					1289					1290

- CHANGED OIL -

ND = Not Determined.

data that, from the time of the oil change to the end of test, the recharge oil had accumulated only 154 hours of usage. With this in mind, it is significant to note the large increase in lubricant viscosity that occurred within that time frame as well as that during the first 56 test hours with the initial charge. In both cases, the oil changed from SAE grade 30 to at least grade 50, with the recharge oil reaching well in excess of grade 50 by the end of test. However, as indicated by the large increase in coagulated insolubles, the oil thickening was due primarily to the accumulation of particulates, principally carbon, rather than to oxidation. This is confirmed by comparing the infrared spectra of the lubricant at zero, 70, 140, and 210 test hours. These spectra are presented in Figures 3, 4, 5, and 6, respectively. While the XRF analyses for metals disclosed significant and rather rapid accumulations in oil samples from both the initial 56 test hours and after recharge, these increases did not appear to be consistent with the measured wear of the engine cylinders and piston rings. Apparently, some of the iron originated from other ferrous engine components such as the gear train, shaft journals, etc. In any event, had the oil not been changed at 56 test hours, it is questionable whether the test could have been completed to 210 hours before degradation of the REO 203 lubricant would have become critical with respect to engine distress due to particulate contamination.

IV. Comparison of Cyclic Endurance Tests Using DF-2 and Crude Oil

As part of another project, a 210 hour wheeled-vehicle cyclic endurance test was run using reference DF-2 and REO 203 (ref-5). The results of the crude oil test will be compared with the DF-2 test results to determine the relative degradation in engine conditions when crude oil was used as the fuel.

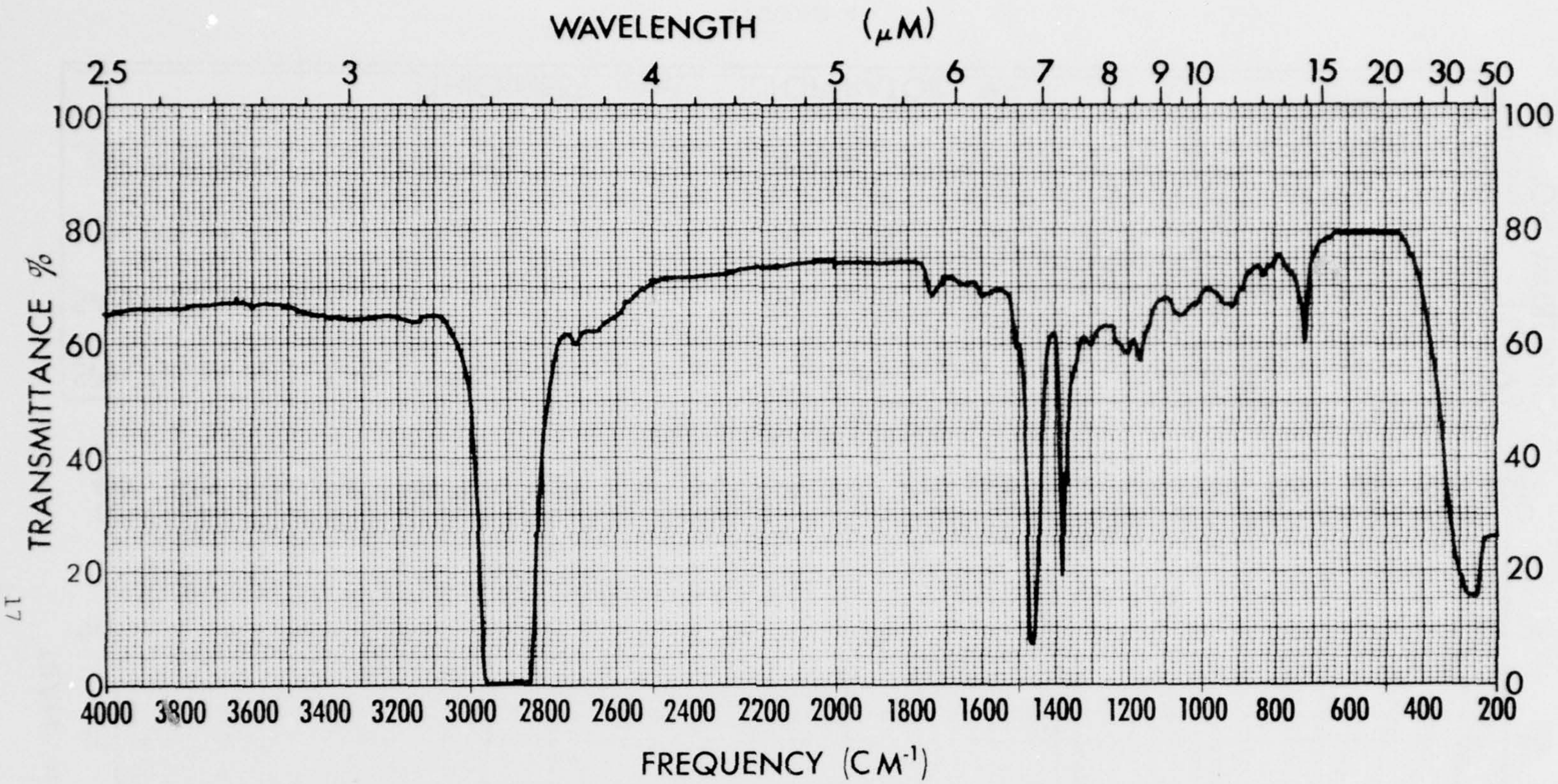
The average operating conditions for both tests are shown in Table 10.

TABLE 10. AVERAGE OPERATING CONDITIONS

	DF-2	AL-6846
Speed, rpm	2600	2600
Obs. Power, kW	88	73.6
Fuel Rate, kg/h	30.2	26.9
BSFC kg/kW-h	0.343	0.365
Oil Sump, °C	114	107
Exhaust Temp, pre turbo, °C	600	615
Oil Consumption, kg/h	0.13	0.06

While the crude oil test had lower power output, much of this was apparently caused by poor fuel delivery as opposed to poor combustion efficiency. This is evidenced by the lower fuel rate with crude oil; however, the BSFC using crude oil was only slightly higher than when DF-2 was used.

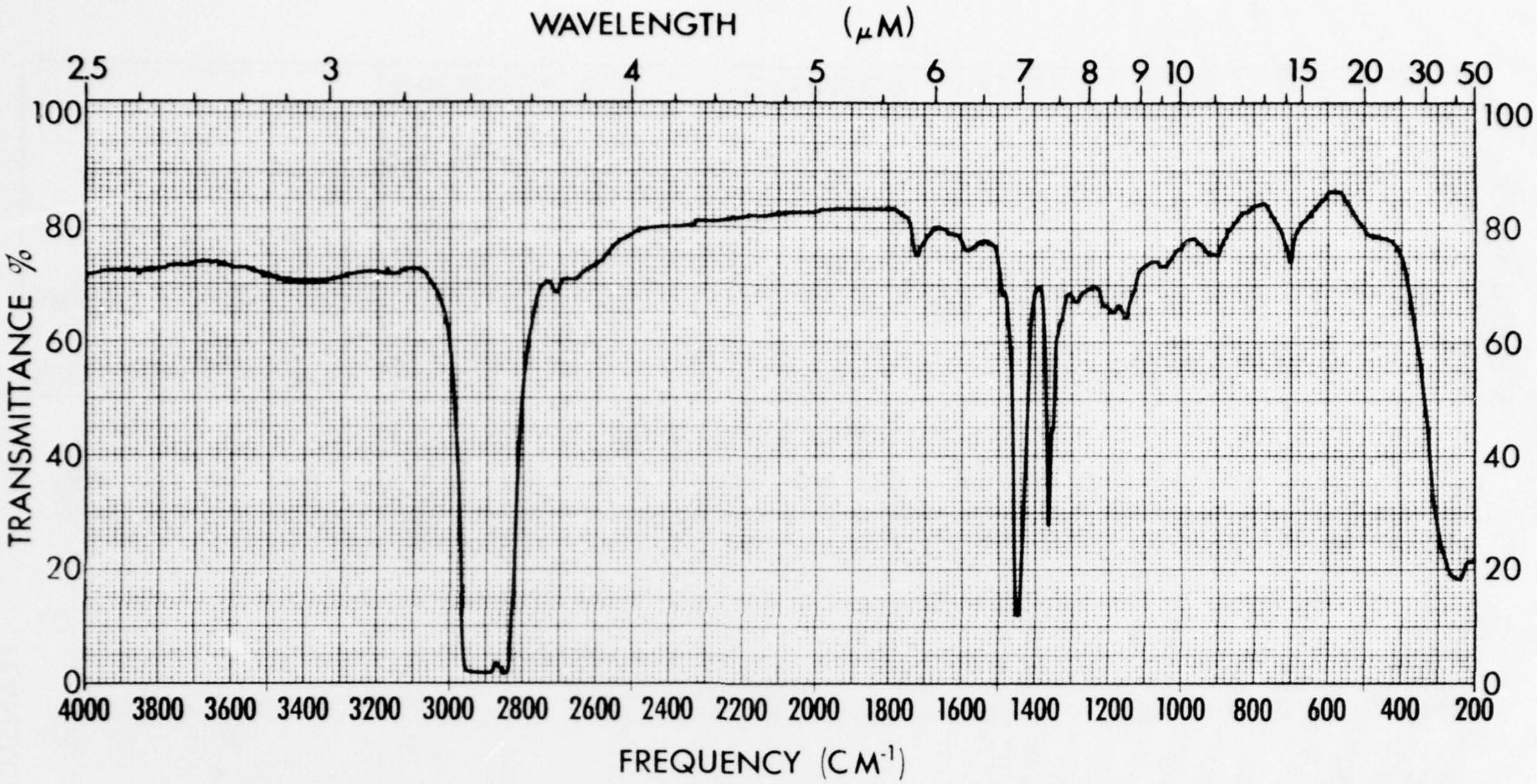
The comparative piston cleanliness ratings are shown in Table 11 which clearly reflect the increased deposits caused by crude oil use.



SPECTRUM NO. 1350	ORIGIN	LEGEND	REMARKS
SAMPLE REO-203		1.	
NEW (0 TEST HOURS)	PURITY	2.	
	PHASE	DATE 11-29-78	
	THICKNESS 0.025	OPERATOR D.B.	

SPECTRUM NO. 1350
SAMPLE REO-203

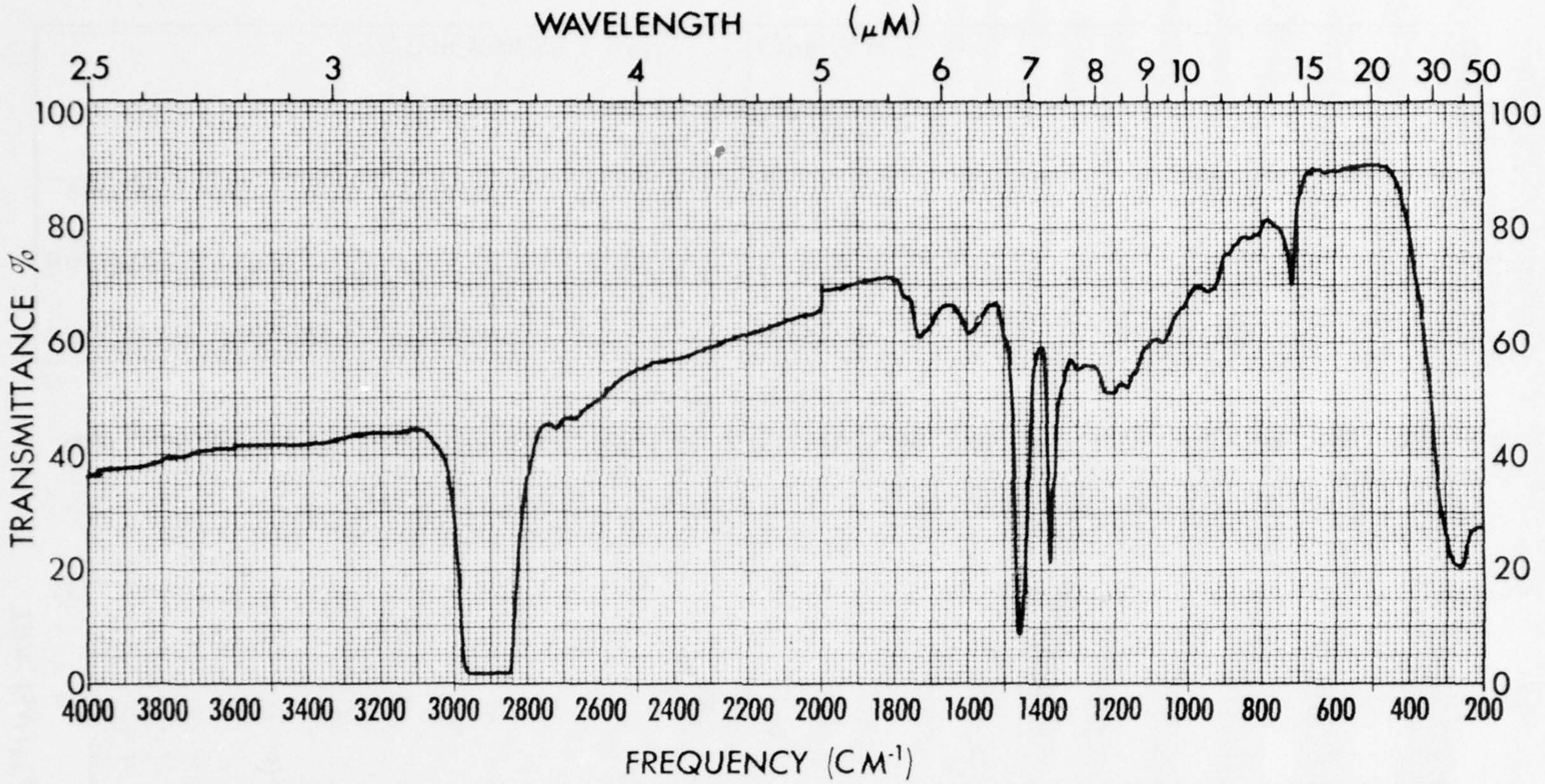
FIGURE 3



SPECTRUM NO. 1288	ORIGIN	LEGEND	REMARKS
SAMPLE REO-203		1.	
70 TEST HOURS	PURITY	2.	
LDT-465-1C ENGINE	PHASE	DATE 9-14-78	
	THICKNESS 0.025	OPERATOR M.G.	

SPECTRUM NO. 1288
SAMPLE REO-203

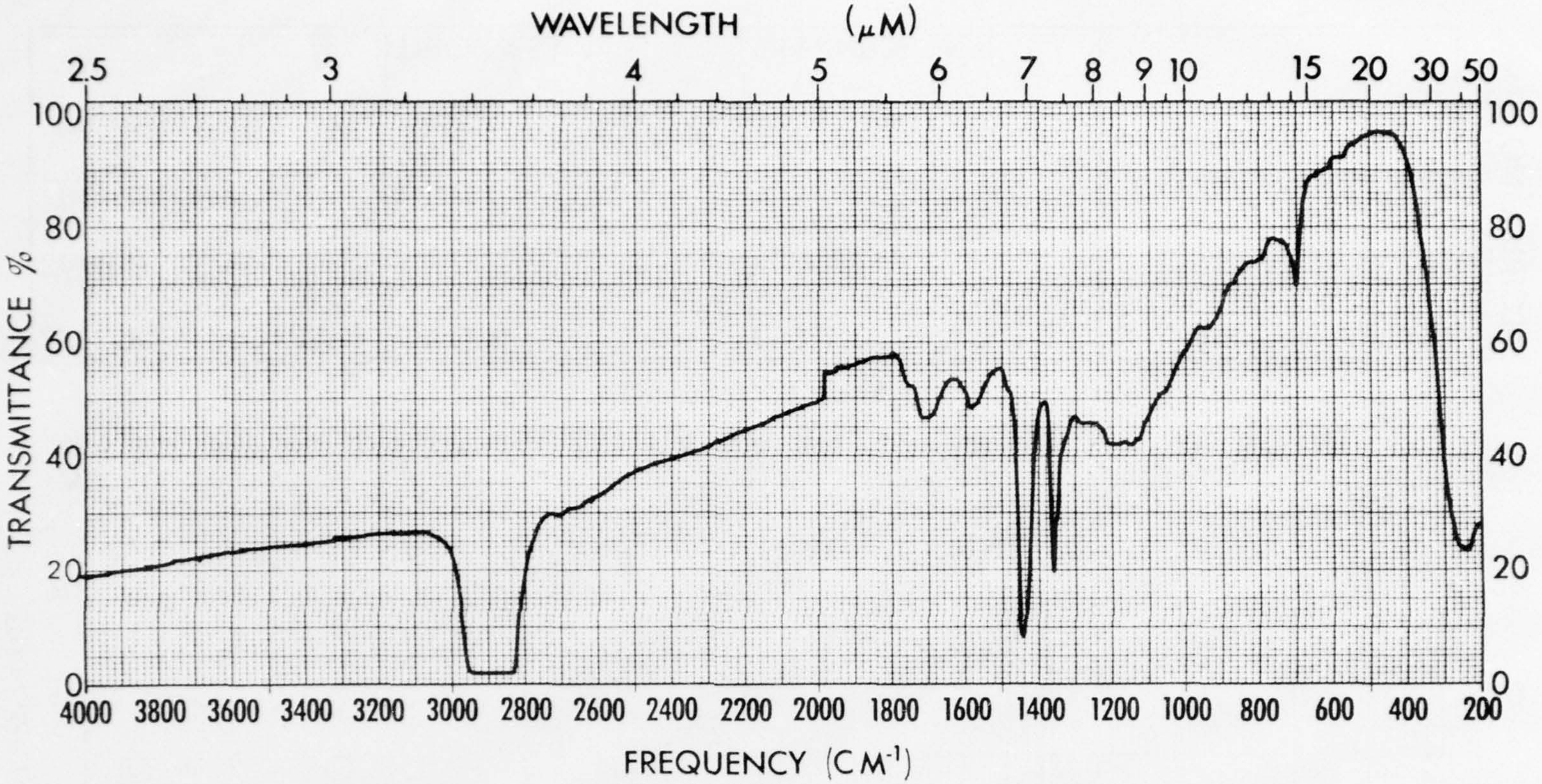
FIGURE 4



SPECTRUM NO. 1289	ORIGIN	LEGEND	REMARKS
SAMPLE REO-203		1.	
140 TEST HOURS	PURITY	2.	
LDT-465-1C ENGINE	PHASE	DATE 9-14-77	
	THICKNESS 0.025	OPERATOR M.G.	

SPECTRUM NO. 1289
SAMPLE REO-203

FIGURE 5



SPECTRUM NO. 1290	ORIGIN	LEGEND	REMARKS
SAMPLE REO-203		1.	
210 TEST HOURS	PURITY	2.	
LDT-465-1C ENGINE	PHASE	DATE 9-14-77	
	THICKNESS 0.025	OPERATOR M.G.	

SPECTRUM NO. 1290
SAMPLE REO-203

FIGURE 6

TABLE 11. PISTON CLEANLINESS RATINGS*

	DF-2	AL-6846
Minimum	236	332
Maximum	320	465
Avg of 6 cylinders	280	428

*weighted total deposit, where 0=clean and 900=max. deposit.

There was no overlap in ratings as the dirtiest DF-2 piston still had less deposit than the cleanest crude oil piston. The average of all six cylinders using crude oil was 48% of maximum deposit while the six DF-2 pistons averaged only 31% of max. deposit. The ring supporting carbon deposit data for the top and number 2 groove are presented in Table 12. Again, the crude oil pistons had a much higher deposit level.

TABLE 12. PISTON GROOVES, AVERAGE % RING SUPPORTING CARBON

Groove	DF-2	AL-6846
Top	0	34
No.2	0	81

The comparisons of average compression ring deposits are presented in Table 13.

TABLE 13. COMPRESSION RINGS, AVERAGE % DEPOSIT

Ring	Tube Deposit	DF-2	AL-6846
1	Lacquer	1	6
	Carbon	33	26
2	Lacquer	3	18
	Carbon	33	18
3	Lacquer	88	8
	Carbon	1	33

The use of crude oil did not appear to cause excessive ring deposits. Piston ring condition is summarized in Table 14. Considering ring face

TABLE 14. PISTON RING CONDITION

	DF-2	AL-6846
Freedom	All free	All Free
Burning	Cyl. No. 2 had some burning. All others normal.	All Normal

burning, the crude oil test resulted in acceptable condition, while there was some burning in one cylinder during the DF-2 test. No rings were stuck during either tests.

Engine wear was much more severe when the engine was fueled with crude oil. As shown in Table 15, the average ring gap increase was greater when crude oil was used. The average cylinder bore increase was

TABLE 15. AVERAGE PISTON RING GAP INCREASE, mm

	DF-2	AL-6846
Top Ring	0.103	0.169
No. 2 Ring	0.070	0.098
No. 3 Ring	0.046	0.089
No. 4 Ring (Oil)	0.073	0.301

also greater with crude oil fuel as shown in Table 16. The increased wear when crude oil was used as the fuel was probably directly related to the rather high sulfur content (1.7%) of AL-6846.

TABLE 16. AVERAGE CYLINDER BORE INCREASE, mm

	DF-2	AL-6846
Front/Back	0.009	0.016
Thrust/AntiThrust	0.012	0.025
Average of Both	0.011	0.021

The comparative end of test used oil analyses (Table 17) showed greater oil degradation in 154 hours using crude oil as fuel than in 210 hours when DF-2 was used.

TABLE 17. USED OIL ANALYSES (REO 203)

	Method	DF-2	AL-6846
Test Hours on Oil		210	154
K. Vis, cSt, 38°C	D 445	195.8	309.6
K. Vis, cSt, 99°C	D 445	17.61	31.66
TAN	D 664	4.8	8.8
TBN	D 2896	4.5	1.5
Insolubles, w%	D 893		
Pentane B		2.89	10.85
Benzene B		2.29	9.48
Elements, ppm by XRF			
Fe		90	380
Cr		10	1
Cu		0	65
Pb		0	90

Compared to the DF-2 test, the used oil from the crude oil test had the following significant differences:

- much higher concentration of wear metals
- large amounts of insolubles
- increased oil viscosity
- higher acid number/lower base number

V. Conclusions

Within the limited scope of these evaluations of crude oils as alternate fuels in the LDT-465-1C multifuel engine, it may be tentatively concluded that:

- Any of the crudes tested could be used in the LDT-465-1C, but only on a short-term emergency basis, and provided that normal power output and fuel economy, as with DF-2 were not required over the speed range of 1400 to 2600 rpm.

- Compared to DF-2, the performance of North Alazan crude (AL-5250) was the most attractive and that of Pearsall crude (AL-6846) was the least attractive of the four Texas crudes, with respect to both available power output and specific fuel economy.

- No engine starting problems were experienced with any of the crudes.

- In the 210-hour cyclic endurance evaluation of AL-6846, the measured engine wear and deposition levels were significantly degraded from the excellent levels observed when DF-2 fuel was used. The full-rack brake power, which initially was about 17 percent lower than that with DF-2, declined an additional 12 percent by the end of the test, while the BSFC increased about 13 percent, or 23 percent above normal with DF-2. The used oil was significantly degraded, which indicates shortened oil change intervals would be appropriate when fueling with crude oil.

VI. Recommendations

It is recommended that additional RDTE effort be performed to determine the effects of direct crude oil utilization in other full scale U.S. Army engines. While this endurance test provided an indication of engine condition degradation when a high sulfur, low gravity crude oil was used, additional endurance test information is needed for other crudes so that a matrix of crude properties versus expected engine condition could be developed for field use. Also, additional effort is needed to examine the feasibility of using field portable mini-refining (crude oil topping) units. Use of these units would lessen crude oil severity and lengthen potential engine life in times when standard fuels are not available.

VII. Acknowledgement

The authors wish to acknowledge the guidance and assistance received from Mr. S.J. Lestz (USAFLRL) and the careful attention to detail provided by the chemistry and engine laboratories at USAFLRL. Special recognition is made of Mr. E.R. Lyons who provided the expert engine deposit ratings.

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